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ATOMIC WEAPONS RESEARCH ESTABLISHMENT

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AWRE REPORT No. T 10/60

On the Resuspension in the Atmosphere of Radioactive or Other Fine Particulate Material Deposited on the Ground

K. Stewart

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A.W.R.E.,
Aldermaston, Berks.

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United Kingdom Atomic Energy Authority

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1. INTRODUCTION

The possibility that the resuspension of deposited radioactivity could give rise to an inhalation hazard has long been recognised. On the early nuclear weapon trials, the radiological hazards from this source and from the γ radiation field were carefully determined. It was found on both the Hurricane and Totem trials that the potential hazard from the inhalation of resuspended fission product fallout was insignificant in comparison with that from the external γ radiation, and so measurements of the latter only were sufficient for health control surveillance purposes.

However, when the contamination is due to a long lived radioactive material which gives rise to no significant external radiation field, the inhalation hazard due to resuspension needs further consideration. The object of this paper is to examine the experimental evidence available and to deduce a representative value for the factor between the contamination level and the airborne activity.

2. EXPERIMENTAL EVIDENCE

The results of the experimental measurements of the airborne activity which were made on a number of field trials are summarised in Tables 1 and 2. The results obtained on the Hurricane [1], Totem [2] and Buffalo [3] series of nuclear tests are shown in Table 1. In addition the results obtained on two Civil Defence trials [4] and a brief summary of some health physics surveillance measurements [5] made during field experiments are also included. In all these experiments the airborne concentration above a contaminated area was measured and the relationship between the concentration and the level of contamination determined. This relationship is the resuspension factor, K, and is defined by

$$K\ (\mathrm{m}^{-1}) = \frac{\text{Airborne Concentration (Curies m}^{-3})}{\text{Contamination Level (Curies m}^{-2})}.$$

On a US trial [6], which had as its object the study of the dispersal of plutonium (and uranium) from a simulated warhead as the result of detonation of the high explosive, measurements were made over an extended period. These results show that the airborne concentration is not independent of the contamination levels upwind. In experiments reported by Healy and Fuquay [7] a readily identifiable particulate material was employed as a contaminant on selected types of ground surface and the airborne concentrations downwind of the seeded areas were measured. From the results (see Table 2) a factor, F, is deduced, which is defined in the following way

$$\begin{array}{l}\text{Particulate Material}\\ \text{Airborne from Surface (particles/m}^2\text{/sec)}\end{array} = \frac{F^{u^2}}{\rho\, d} \times \begin{array}{l}\text{Particulate}\\ \text{Contamination}\\ \text{(Particles/m}^2\text{),}\end{array}$$

where u is the wind speed in m/sec, ρ is the material density in g/cm^3 and d is the diameter of the particles in μ. From all these results it is quite clear that the amount of any ground deposited material which is resuspended in dust under differing conditions, is likely to be a very variable quantity. This conclusion would be expected on quite general considerations. Thus, the fineness of the soil or sand in the surface layer, the air turbulence and wind speed in the air layer close to the surface, the moisture in the ground and the presence of external sources of agitation (such as moving vehicles) will all affect the amount of material resuspended in the air. Further, the particle size distribution of the dust on which the radioactive or other deleterious material is deposited will be an important factor in determining the fraction of resuspended material which constitutes an inhalation hazard. The largest diameter of particle which is likely to reach the critical parts of the lung is about 10 μ; this diameter is less for high density materials, and for dusts generally is unlikely to exceed 6 μ. Because impaction is the more important mode of deposition in the respiratory system the particle size scales as $\rho^{-1/2}$. Fortunately, particle size measurements were made on some occasions.

2.1 Operation Hurricane

The results obtained in the fallout area on Hurricane form a self-consistent set, except for the two extreme values. The samples of airborne material were measured in terms of β activity, whereas the contamination level was determined by a γ radiation survey. The known relationship between the β and γ activity of fission products permits the results to be compared, although there may be some uncertainty in individual figures because the γ dose-rate depends on the area of contamination and the terrain. The results obtained at the same time for the amount of α activity resuspended are in close agreement with values estimated from known detail of the weapon and its performance. This firing occurred underwater and the fallout was mainly in a finely divided form. An average value of 1×10^{-5} m^{-1} was obtained for the resuspension factor K under conditions when the ground was disturbed mainly by wind and natural turbulence, but, there may have been some instrument recovery operations in progress.

It is noteworthy that, apart from decay, the fallout pattern, determined by γ survey was not markedly changed over a period of more than a year (405 days). The observed decay in the γ radiation dose-rate over the period from the time of the original surveys to the survey about a year later corresponds quite closely to that calculated for the fission products. Thus, even though there was some drifting of sand and the area of the survey was effectively much less because of decay, this result shows that only a small fraction could have been removed by the wind. This result is all the more significant since a cyclone and a total of 16 in. of rain are reported for the period. The uncertainties inherent in the measurements mean that it is not possible to estimate accurately the amount removed by weathering, but it is unlikely to be much greater than 10%.

2.2 Operation Totem

The results obtained on the Totem trials show that the problem was examined carefully at the time. One of the relevant differences between Hurricane and the later trials in the Australian desert is that for the latter the conditions were dry and a considerable fraction of the fallout was on, or in, material that had been fused. This may account for some of the very small values for the resuspension factor.

The results obtained at the back, and over the tailboard, of a Landrover vehicle in motion show that under these rather severe conditions, the maximum value is only about 1×10^{-5}. Carter, in the report on the Totem measurements, points out that the activity measured depended on the position of the sampling device at the back of the Landrover. It is noteworthy that the two results obtained on D + 7 in which the orifice of the sampler projected just above the tailboard, are comparable with those obtained on D + 4. The wind conditions for the two days are not reported, but a difference in wind strength might well account for the different concentrations observed within the back of the Landrover on the two days.

The evidence that the bulk of the activity is not rapidly redistributed by natural disturbance, nor appreciably by actual stir-up of the surface, is shown by the observed γ dose-rate measurements for the two days. The differences in the γ dose-rates on D + 4 and D + 7 correspond to fission product decay, and do not suggest that a significant part of the airborne material raised by vehicles between D + 4 and D + 7, or by natural erosion over this period, was blown away. Measurements of the amount of airborne radioactivity at clean sites downwind from the active area produced by the first round showed that very little was transported any distance on dust.

Summarising, we note that three different survey operations on foot, without vehicles moving in the vicinity, lead to a mean resuspension factor of 3×10^{-7}, or if four of the total of 33 results are omitted, the value is about 1×10^{-7}. Whereas, in the dust cloud thrown up by a Landrover the mean value is about 1×10^{-5}. It must be pointed out here that the roads on the trials sites in the Australian desert were formed by grading the ground and the surface did not contain any binder such as bitumen. The dust clouds raised by vehicles were heavy and were only typical of such desert conditions. However, it cannot be assumed that the dusty nature of the terrain in the Australian desert necessarily produces severe conditions because it may be argued that the activity deposited initially on the surface soon becomes mixed in a considerable amount of loose sand and earth as the naturally stabilised surface is broken down. This might lead to only a small fraction of the activity being available for resuspension.

2.3 Operation Buffalo

The two results obtained on Buffalo are principally of interest because of the particle size measurements. The gross resuspension factors are similar to those obtained on Totem and the particle size measurements suggest that about 20% or less of the airborne material could constitute an inhalation hazard.

2.4 US Trial - Plutonium Contamination Due to a One Point Explosion

In this trial (in Spring, 1957) a warhead containing a representative amount of plutonium was placed on the ground and the H.E. initiated at a point underneath. The contaminated area was determined by analysis of some 4000 deposition samples. The study of the condition of the contaminated area forms a continuing project. From the analysis of carefully collected soil samples it is known that the bulk of the activity is in the top ½ in. of soil and measurements of the distribution in depth made initially at 6 months after firing and subsequently 18 months later gave similar results. About ½ in. of rain fell during the first 6 months and this may have determined the extent of the penetration into the soil. It has been estimated that only from 4 - 9% of the original contamination had been removed by erosion.

For the observations on resuspension three sites were chosen with contamination levels of 560, 40 and $2.6 \mu g$ Pu/m^2. The results obtained over a period of 133 days showed that the concentration of airborne material was variable, depending on wind direction and speed, but on the average showed a continual decrease with time which may be expressed as a half-life of about 37 days. This half-life would be expected to be characteristic of the terrain and meteorological conditions existing at the Nevada Test Site, and also shows that the fine particulate material exposed to natural erosion is steadily depleted or fixed. This is borne out by the fact that there is apparently no direct relationship between the contamination level at the sampling site and the activity in the sample, but rather a relationship with the extent of the contaminated area up-wind. During the experiments the wind blew across the heavily contaminated zone towards the areas of lower contamination for a large proportion of the time, which explains why a relatively high value was observed for the sample collected in the region of over $2.6 \mu g/m^2$. This result is examined in more detail in the discussion.

2.5 Civil Defence Trials

The two experiments carried out at the Civil Defence School at Falfield, Gloucester, are also of considerable importance and were the first investigations of the problem. The dust was contaminated with known amounts of carrier free I-131. Both the atmospheric dust loading and the airborne activity were measured. The first experiment was carried out in a confined space, approximately 8 ft × 12 ft × 7 ft in height in which a rescue worker has to work his way from front to rear in search of casualties, passing back some of the debris by hand and shovelling the rest. A resuspension factor of about 2×10^{-4} was measured and a total dust loading of 110 mg/m^3. In the second trial, a collapsed house was used in which rescue workers were trained in debris clearance in the open by hand during a systematic search for trapped casualties. The resuspension factor was 2×10^{-6} and the dust loading in the atmosphere about 10 mg/m^3. The dust used in these experiments was a brick and plaster dust from a bombed site in Bristol and was quite fine, with a median particle size of less than 1 μ. A portion of the dust was treated initially with the carrier free I-131 solution and this dust was then spread over the experimental area. The difference in operations and the distribution of activity in the bulk of the dust and debris during each experiment would account for the different ratios of airborne activity to dust loading. Both trials were carried out under dry conditions in May. These experiments are of interest as lending general support to the values obtained in other experiments. They are, however, not directly applicable to the general problem because of the conditions, the first being in an enclosed space and both being particularly dusty operations.

2.6 Health Physics Surveillance

The last set of results given in Table 1 was obtained during Health Physics control of clean-up operations in the firing zones after certain kinds of supplementary trials. The majority of the samples were obtained at a height of about 1 ft above the ground. Since the observed particle sizes are quite large, the fraction contributing to a possible inhalation hazard is small.

2.7 Trials with Small Areas Contaminated with an Identifiable Particulate Material

In two series of experiments reported by Healy and Fuquay [7], known amounts of particulate material were deposited on circular areas of different kinds of ground surfaces. The areas were quite small; 3 m radius in one series and 1.5 m in the other. The tracer material was a fluorescent particulate with a mass median diameter of 7 μ and a total size range of 1 - 35 μ. In the first series the concentration of airborne material due to natural erosion was measured at 40 m and 61 m downwind at a height of 0.5 m. The results are summarised in Table 2. Detail of how the samples were obtained and analysed is not given but it is stated that any depletion of the source was neglected in the estimation of F. Both wind speed and particle size were taken into account in estimating F from the experimental results, and it was found that although the observed airborne concentrations were spread over a range of two decades, the values of F were sensibly constant (1.1 to 6.8×10^{-7}). Therefore, these results lend support to the hypothesis that the amount of material resuspended is proportional to μ^2. However, it should be noted that the wind speed was measured at a height of 2 m, whereas the relevant wind speed is that at the surface and hence the implication is that the wind profiles were similar at the time of each measurement. In the second series the effect of a short period of rain (about 2 hr) was observed. The results appear to be somewhat inconsistent, there being a reduction of about three in the value of F in the case of furrowed soil, whereas for grass it is greater than for dry conditions. The quoted average for the damp period is 0.6×10^{-7} and for the dry conditions 2×10^{-7}. These average values suggest an overall reduction by rain of about 3.

3. DISCUSSION

It was observed on both Hurricane and Totem that there was no significant shift of activity on the ground due to resuspension in the air and subsequent dispersal by the wind. A similar result was reported for the US trial and in this case the distribution in depth was also found to be constant over the period 6 months to 2 years after deposition. In all these cases the surface was largely undisturbed as the result of human activity, but there was continual natural erosion. From examination of these results it appears that the deposited material rapidly becomes mixed in the top few millimetres, perhaps centimetre, of soil or sand and a considerable part attached to coarse particles. There may remain up to about 10% which is near the surface and can, when once airborne, remain suspended for a considerable time to create at least a potential inhalation hazard. This material may be steadily spread over an ever wider area, which process would lead to the apparent half-life of about 37 days found in the case of the Nevada Test Site. A process of fixation to the coarser particulate material in the top surface layer would also account for the permanence of the contamination and the reduction of the fraction which can be resuspended. However, there does not appear to be any experimental evidence to support this idea, except in the case of cultivated soil. It is necessary, therefore, in any complete treatment of the problem, to take into account the change in the contamination pattern with time. Clearly, this is a very difficult problem and a complete solution is not attempted in this paper. Part of the difficulty lies in the lack of a proper understanding of the mechanisms which control the resuspension of surface material, particularly the very fine particles which may constitute an inhalation hazard. The studies reported by Bagnold and by Chepil suggest that coarse material is first moved by the wind and the subsequent disturbances lead to the suspension of other material. It appears reasonable to assume that the amount of hazardous material which becomes airborne from any particular area of surface will be proportional to the amount of contaminant present, may be regarded as originating from a ground level source, and be considered in accordance with Sutton's theory for the travel of smoke clouds, provided allowance is made for re-deposition. If the surface contamination on particles of diameter d at time t and position x, y is given by S(s, y, t, d), then the rate at which material becomes airborne from an element of area (dx,dy) may be written as fSdxdy, where f is constant for a given set of meteorological conditions and surface structure. Healy and Fuquay have proposed a relationship for f of the form

$$f = F\frac{u^2}{\rho d}, \qquad \text{...............(1)}$$

where u is the wind speed, d the particle diameter, ρ the density of the material and F is a constant. This relationship for taking into account the effect of wind speed and particle size is a grossly over-simplified one and may not adequately represent the real situation. Chepil [8] has defined several particle size ranges for soil depending on the ease or otherwise with which they are eroded. Thus, particles in the size range 50 - 500 μ diameter are said to be highly erodible, whereas those smaller than 20 μ are non-erodible except at very high wind speeds Bagnold [9] has reported a similar situation in the relationships of dust and sand movement. Thus, in the absence of human, animal or vehicular traffic, the principal way in which the finely divided material can become airborne is by the process of saltation. In this the grains of sand or soil (mainly in the 50 - 500 μ size range) are set in motion by the wind and subsequently cause surface disturbances on impact. There appears to be a critical wind speed below which the surface remains undisturbed, but above which sand grains begin to move and build up the saltation process. Once this is established, both fine and coarse material will become airborne. The threshold velocity to move sand (200 μ diameter) is about 2.5 m/sec at 0.3 cm above the surface. Hence an alternative simple form for the relationship would be

$$f = F_1(u - u_t)^2, \qquad \text{...............(2)}$$

where u_t is the threshold wind speed for surface movement and F_1 incorporates the other properties of the surface. However, the data available are inadequate to test a relationship of this kind. In the following examination of the airborne concentration and rate of removal of activity, we shall examine the effects of particle size on the rates of removal and the deposition of the material. The marked variations in the amount of material resuspended may well reflect the changes in wind speed but, because the measurements of micrometeorological factors were inadequate, little analysis can be attempted.

It was observed on both Hurricane and Totem and on the US trial that there was no significant shift of activity due to resuspension in the air and subsequent dispersal by wind. It may be argued that at Totem this was due to the nature of the fallout, but on Hurricane the fallout was not in the form of fused granules and the natural dust was made up of sand and broken coral. In the case of the US trial in Nevada the soil was essentially fine particulate material. If the surface contamination level may be assumed to remain approximately constant, then it is possible to deduce the order of magnitude of the resuspension factor which will permit this to be realised. It will be assumed that the cross-wind dimension of the area is large so that the infinite line source theory of Sutton may be applied. If the contamination level is S $\mu c/m^2$, then the rate at which material, more precisely of a particular size, becomes airborne may be assumed to be A (=fS) $\mu c/m^2/sec$. The elemental area of unit cross-wind width and downwind length dx may be regarded as a line source dQ (=Adx) $\mu c/m^2/sec$). This particulate material will be assumed to possess a terminal velocity V_D if the particles are large enough, or a deposition velocity V_D if deposition is determined more by turbulence and impaction than by sedimentation. In both cases the rate of deposition, D, will be given by $V_D \chi(x,O)$, where $\chi(x,O)$ is the airborne concentration at range x and ground level ($z = \theta$). It has been shown by Chamberlain [10], in the case of a source at ground level, that if deposition is taken into account, the source strength Q appropriate to any range x is given by the relationship

$$Q_x \quad Q_o \exp -\left(\frac{4V_D x^{n/2}}{\pi^{1/2} n u C_z} \right), \qquad \ldots\ldots.(3)$$

where x is the range in metres, u is the wind speed in m/sec, C_z is the coefficient of eddy diffusion in $m^{1/8}$ and n is a constant determined by the atmospheric stability with the value of 0.25 for "average" or zero temperature gradient conditions. Therefore the airborne concentrated at range x from the source dQ will be given by

$$d\chi(x,o) = \frac{2dQ \exp\left[-\dfrac{4V_D x^{n/2}}{\pi^{1/2} nuC_z}\right]}{\pi^{1/2} uC_z x^{1=n/2}}$$

$$= \frac{2A \exp\left[-\dfrac{4V_D x^{n/2}}{\pi^{1/2} nuC_z}\right] dx}{\pi^{1/2} uC_z x^{1-n/2}} .$$

On integration we obtain the result

$$\chi(x,o) = + \frac{A}{V_D} \left[e^{-Y}\right]_{x_1}^{x_2}, \qquad \text{......(4)}$$

where

$$Y = \frac{4V_D x^{n/2}}{\pi^{1/2} nuC_z}$$

and x_1 and x_2 are the upwind distances of the boundaries of the contaminated area from the position of interest x. If this position is within the contaminated area, then $x_2 = 0$. In this case

$$\chi(x,o) = \frac{A}{V_D} (1 - e^{-Y}). \qquad \text{..........(5)}$$

The rate of deposition will be $V_D\chi$ and as the rate of resuspension is A, the net loss from the surface at x is given by Ae^{-Y}. If this term is to be small the value of Y must be greater than 1. By inspection of equation (4) it is found that the terminal or deposition velocity is the most important variable. The range x is of minor importance because the term $x^{1/8}$ increases only slowly with x. For deposition by turbulence and impaction a reasonable value for V_D is 2 cm/sec and assuming a wind of 5 m/sec, a value for Cz of 0.12 and putting $x^{1/8} = 2$ the value of Y is found to be 0.6. Hence, for fine dust of this kind, 10 - 20 μ diameter, significant loss by dispersal downwind would be expected. For a terminal velocity of 20 cm/sec, corresponding to about 50 μ, the removal would be very slow. The resuspension factor, K, is given by

$$K = \frac{\chi(x,o)}{S} = \frac{f}{V_D}\,(1 - e^{-Y}), \qquad \ldots\ldots (6)$$

and the decrease of K (in terms of f) with increase of particle size because of loss by redeposition, is shown in the Table 3 for the values of Cz, u and x quoted above.

For the circumstances which have been specified, viz. a large area of contamination, initially uniform and a steady but slow travel of material and contamination in one direction, it is reasonable to assume that these steady state conditions imply an essentially uniform contamination level except in the vicinity of the upwind edge. However, this level will decrease with time and the rate of removal of activity will be given by

$$\frac{dS}{dt} = -fSe^{-Y},$$

on integration this leads to

$$S = S_o \exp(-fte^{-Y}), \qquad \ldots\ldots (7)$$

and the half-life, $t_{1/2}$, will be equal to $\frac{0.693}{fe^{-Y}}$.

Some estimates of half-life are given in Table 3. It is found for fine dust that if the resuspension factor K has the value 1×10^{-5}, the half-life of the deposit would be about a month. This is similar to the US experimental result. These results are also in agreement with the observations obtained on weapon trials in Australia. In those cases where a resuspension factor of about 1×10^{-5} was obtained but the activity remained in situ for considerable periods, a large fraction of the resuspended materials was probably on coarse particles of 50 μ and larger. The two measurements made on Buffalo, in which the particle size distributions were determined, support this conclusion.

So far the contamination has been assumed to be uniform, which is a condition unlikely to be met in practice. Indeed, in the active area formed on the US trial, the contamination levels were from about 2000 $\mu g/m^2$ down to 5 $\mu g/m^2$ for the closed contours and to much lower levels in the area beyond. Resuspension studies were carried out in areas where the total surface contamination was 560, 40 and 2.6 μg/m², but this wide range of values was not reflected in the samples of airborne activity. The positions were, from the aspect of the prevailing wind, downwind of the most active area. The theory already developed can be applied to this situation, but for ease of calculation the contamination pattern has been much simplified. It is found that the fallout area may be idealised to one with a cross-wind dimension of 800 m and a downwind profile given by

$$2000 \exp - \frac{x}{400} \ \mu g/m^2 \qquad (x \text{ in m}).$$

At a position distance P downwind of the upwind edge (or effective peak in contamination), the airborne concentration on the mid-line of the rectangular zone and at 5½ ft above ground level will be given by

$$\frac{4 \times 10^3 f}{\pi^{1/2} u C_z} \int_0^P e^{-\frac{x}{400}} . e^{-\frac{4V_D x^{n/2}}{\pi^{1/2} n u C_z}} . e^{-\frac{z^2}{C_z^2 x^{2-n}}} \, dx \qquad \ldots.(8)$$

where X = P - x. This expression is only true for a short time because, once the airborne transport of activity is established, the downwind profile will change. However, the main object of the calculation is to show that airborne concentration at any point is affected significantly by the extent and density of the upwind contaminated area. It is found that, as the extent of the contaminated area upwind increases, the fraction of the airborne material which comes from the area immediately upwind of the position of interest decreases. Thus, at 550 and 1000 m from the upwind edge about half the airborne material comes from the area within 10% of these ranges immediately upwind of the site. At 2000 m the fraction is only about 1/4. The results are summarised in Table 4. The ratio between the extreme levels of contamination is about 40 and in the airborne concentrations about 20. This is in general accord with the US observations although the observed ratios were 200 and 7 respectively. If the value for f which corresponds to a half-life of about 30 days (see Section 3) is introduced, it is possible to estimate the doses which would be inhaled in a day. These are of the same order as those observed experimentally on the US trial. The information available on the US trial is not sufficient to enable a detailed comparison to be made. The upwind ranges and contamination profile have been estimated from the contamination contours available.

The results reported by Healy and Fuquay show that the constant F in equation (1) has a value of about 2 to 3 × 10^{-7} for several surfaces, i.e., grass, ploughed (furrowed) land and rock. The wind speeds were in the range 1 - 10 m/sec so that, provided allowance was made for the mean size of particle collected during each experiment (the particle density will be constant), these results give considerable support to the concept that resuspension depends, approximately, at least on u^2. By combining equations (1) and (6) the relationship between K and F is found to be

$$K = \frac{Fu^2}{\rho d V_D} (1 - e^{-Y}).$$

The terminal velocity of a particle of diameter 7 μ and density 4 g/cm^3 (i.e., assuming the fluorescent material to be ZnS) is about 0.6 cm/sec and a deposition velocity of this order, or perhaps as high as 2 cm/sec, may be assumed to be reasonable. If $F = 2 \times 10^{-7}$, then K is found to be about 5×10^{-6} for a wind speed of 5 m/sec. Therefore, the results of Healy and Fuquay indicate that for a particulate material with a mass median size of 7 μ, the value of K would be in the range 10^{-5} to 10^{-6} for quite a wide range of surface and meteorological conditions. Of this material, only that fraction in the size range smaller than about 7 μ would constitute an inhalation hazard.

4. CONCLUSIONS

As would be expected from elementary considerations it has been found that the airborne concentration at any position depends on both the extent and the intensity of the contaminated area upwind. The experimental results obtained on the US trial in which plutonium was dispersed and the theoretical estimates in this report both indicate that the extent of the upwind area is rather more important than an isolated area contaminated to a relatively high level unless this is immediately upwind of the sampling position.

As it is found that the actual samples of airborne activity show quite marked variability due mainly to variation in the wind and surface conditions, it is not unreasonable to argue that a simple resuspension factor taken in conjunction with a representative value for the contamination level for a particular area can provide a useful indication of the degree of hazard regardless of the wind. The representative value for the contamination level would be an average figure taking into account the direction of the prevailing wind and extent and nature of the contaminated area.

From the experimental results examined it appears that a resuspension factor as large as 10^{-5} is likely to be appropriate under certain conditions. In particular it would be appropriate to dry dusty terrain where erosion occurs to some degree and to situations where there is vehicle movement on dry dusty roads. Higher values, namely, 10^{-4} to 10^{-3}, have been observed under rather special conditions at some trials, but consideration of the rate of removal of activity suggests that for fine dust such a degree of resuspension would lead to widespread dispersal of the contaminant in a few days so that such high values could not persist. Under other circumstances values as low as 10^{-7} have been observed. The results reported by Healy and Fuquay suggest that a brief period of rain may reduce the amount resuspended by a factor of about 3. Under continuously damp conditions, such as are common in the UK, it is to be expected that the reduction would be rather greater, perhaps to a value of 10^{-6}. In any case the crude theory developed shows that if a resuspension factor of 10^{-5} applies to fine dust, up to about 20 μ diameter, this material is likely to be continually removed by the wind and the effective half-life of the erodible material would be of the order of 1 month. If the material is coarser than 20 μ, resuspension to this degree may take place; but little, if any depletion of the source will occur and neither will an inhalation risk exist. Therefore, provided the material resuspended from the ground surface is not predominantly in the hazardous size range (< 6 μ diameter) the value for K of 10^{-6} would provide a conservative estimate of the inhalation hazard.

The observed reduction in effective contamination level by weathering is of considerable importance. Movement in such an area may bring contaminated material to the surface and, in effect, tend to offset this reduction.

The experimental evidence is far from comprehensive and observations under a variety of conditions have yet to be made. From the simple analysis attempted in this paper it is clear that the circumstances of each experiment must be accurately recorded in detail. The mechanism by which the fine particulate material is raised from the surface is of particular importance. The wind profile and the vertical turbulence, as functions of height above and near to the surface, may be expected to be significant variables to measure in this respect.

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TABLE 1

Summary of Experimental Results on Resuspension of Activity in the Air

Trial	General Circumstances of Measurement	Resuspension Factor	
		Range	Mean
Hurricane	Sample of airborne material obtained without artificial disturbance of ground surface (12 results)	1×10^{-6} to 8×10^{-5} but 10 values lie between values 0.47×10^{-5} to 1.6×10^{-5}	1×10^{-5}
Totem	Random samples collected in region of T1 crater in absence of artificial disturbance of the ground (9 results)	1×10^{-6} to 1×10^{-8}	2×10^{-7} (0.8×10^{-7} if one result at 1×10^{-6} excluded)
	Surveys on C and D roads of grid - no artificial disturbance of ground surface (14 results, with 6 indefinite but measured values all $< 2 \times 10^{-7}$)	1.5×10^{-6} to 1×10^{-8}	2.5×10^{-7} (or 0.8×10^{-7} if one result at 1.5×10^{-6} is excluded)
	Surveys on "Dingo" road - samples collected at back of Landrover in motion (21 results, 10 of which 2 were obtained over the tailboard) on the 4th and 7th days after the first test	On 4th day: 0.8×10^{-6} to 3×10^{-5} On 7th day: 0.6×10^{-6} to 4×10^{-6} On 7th day: 1.6 and 3.1×10^{-5} at tailboard position	1.4×10^{-5} 1.5×10^{-6} 2×10^{-5} at tailboard
	Survey of road to Site C (10 results) on 1st and 2nd days after the second test. Of these, 3 are indeterminate but less than 2×10^{-8} and only 2 are $> 1 \times 10^{-6}$	1×10^{-8} to 2×10^{-6}	4×10^{-7}
Buffalo	Sample collected during an instrument recovery sortie in which the sampler, a cascade impactor, was carried in the driving compartment of a Landrover for part of the time and was outside the stationary vehicle near the working party for the remainder		
	Round 1 (H + 18 hr)	2.5×10^{-5} but only about 10% of the activity was present on particles $< 6\ \mu$ diameter	
	Round 2 (H + 5 hr)	6.4×10^{-5} but only about 20% of the activity was present on particles $< 6\ \mu$ diameter	
Civil Defence Trial at Falfield	Representative brick/plaster dust sample contaminated with I-131 and distributed on greater amount of dust and used during two realistic Civil Defence, bomb-site, recovery trials.		
	1. Enclosed Space		2×10^{-4}
	2. Open Area		2×10^{-6}
Some representative results obtained during Health Physics surveillance of minor experimental trials at Maralinga	1. Uranium (1957) sample collected immediately downwind of crater at: 1 ft above ground 2 ft above ground 1 ft above ground (dust stirred up)		3×10^{-4} 1×10^{-5} 1×10^{-8} Estimated that $< 5\%$ in hazardous size range
	2. Plutonium (1959 Vixen) sample collected at: 1 ft above ground: - dust created by vehicles - dust created by pedestrian	3×10^{-4}, 7×10^{-4} 1.5×10^{-6}, 3×10^{-4}	Particle size mainly 20 - 60 μ; estimated that $< 1\%$ in hazardous size range

Notes: 1. By hazardous size range is meant particles $\leq 10\ \mu$ diameter at unit density. For sand the corresponding size is about 6 μ and for PuO_2 about 3 μ.

2. Particles collected on the first stage of a cascade impactor are sized by direct examination under a microscope.

TABLE 2

Values Observed for F for Two Ranges and Different Wind Speeds

Distance, m	Airborne Concentration, χ particles/m^3	Wind Speed, m/sec	Factor, F $\times 10^7$
40	86	2.7	3.7
	120	3.1	4.3
	28	2.7	1.9
	14	0.9	4.7
	4.6	1.8	1.1
	20	1.8	4.9
	1.4	1.3	6.8
61	9.2	2.7	2.7
	17	2.7	5.1
	16	2.7	5.8
	7.8	2.2	3.6
	1.4	3.6	3.6
	3.2	1.8	2.3
	6.4	1.3	6.8
			Mean 4.1

Notes:

1. In evaluating F the units used were ρ in g/cm^3 and particle diameters in μ.

2. It was assumed that $n = 0.25$ and Cz, Cy = 0.18 for the calculation of χ from a relationship similar to equation (4).

TABLE 3

Estimation of Half-Life of Source of Material for Re-Suspension

Type of Particulate Material	Terminal or Deposition Velocity, m/sec	K, m^{-1}	Estimated Half-Life for Contaminated Zone (days) for:		
			K 1×10^{-4}	K 1×10^{-5}	K 1×10^{-6}
Very fine dust)	0.001	30 f	2.5	25	250
diameter ≤ 1 μ)	0.002	30 f	2.6	26	260
Fine dust up)	0.01	26 f	2.9	29	290
to about 20 μ)	0.02	23 f	3.4	34	340
Coarse dust,)	0.1	10 f	16	160	1600
fine sand ~ 50μ)	0.2	5 f	160	1600	16,000

TABLE 4

Theoretical Estimation of Airborne Concentration Downwind of a Heavily Contaminated Area

Contamination at Point P, $\mu g/m^2$	Integral Term in Equation (8)	Airborne Concentration, $\mu g/m^3$	Dose Inhaled in 1 Day ($f = 3 \times 10^{-6}$)
500	3.57×10^{-2}	65 f	4.7×10^{-3}
160	1.36×10^{-2}	25 f	1.8×10^{-3}
13	1.6×10^{-3}	1.9 f	2.1×10^{-4}

Initial Distribution

Internal

No.	1	DAWRE, Dr. N. Levin
	2	DDAWRE, Mr. E. F. Newley
	3	HSC, Mr. R. Pilgrim
	4	GMO, Dr. J. B. Lynch
	5	SSCTD, Mr. P. A. White
	6	SSFE, Dr. J. A. T. Dawson
	7	SSGS, Mr. D. E. Barnes
	8	TA/DDAWRE, Mr. J. T. Tomblin
	9	AHSC, Dr. K. Stewart
	10	SRI, Mr. N. Pearce
	11	Mr. R. F. Carter, SRI
	12	Mr. J. Hole, SSGS
	13	Mr. W. N. Saxby, SSGS
	14	Mr. D. M. C. Thomas, SRI

External

		AERE, Harwell
No.	15	Mr. A. C. Chamberlain
	16	Mr. N. G. Stewart
		Health and Safety Branch
	17	Mr. F. R. Farmer
	18	Dr. A. S. MacLean
	19	Dr. W. G. Marley
		Medical Research Council
	20	Dr. J. L. Loutit
	21	Dr. E. E. Pochin
		Ministry of Defence
	22	Dr. R. Press
		CEGB
	23	Mr. C. A. Adams
	24	Mr. G. C. Dale